1. **Project Name:** **Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance**

2. **Lead Organization:** Oak Ridge National Laboratory
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Oak Ridge, TN 37831

3. **Principal Investigator:** Gerard M. Ludtka
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4. **Project Partners:** **Cummins Inc** (technical collaboration and specimen fabrication support),
Roger D. England
Florida State University
National High Magnetic Field Laboratory (technical collaboration and facilities/experimental support including an ORISE Summer Faculty Fellowship at ORNL),
Prof. Peter Kalu
Industrial/University interest/communication: Dura-Bar, Timken, Southwire, Cryomagnetics, Inc., and Kettering University.

5. **Date Project Initiated and FY of Effort:** Initiation Date: October 1, 2001, Current: FY03

6. **Expected Completion Date:** September 30, 2004

7. **Project Technical Milestones and Schedule:**

This research and development project is developing a new, high-payoff processing methodology whereby a new class of materials with novel microstructures and superior properties will be achieved in addition to optimizing the current processing of conventional materials. Since essentially all materials have some form of ferromagnetism or paramagnetism, magnetic field processing is directly applicable to a multitude of materials for dramatically influencing phase stability and phase transformations for an alloy or compound. This ability to selectively control microstructural stability and alter transformation kinetics through appropriate selection of the magnetic field strength promises to provide a very robust mechanism to develop and tailor microstructures (even nanostructures) for a broad spectrum of material applications. For this project, ferrous alloys are being studied initially since this alloy family exhibits ferromagnetism over part of its temperature range of stability and therefore would demonstrate the maximum impact of this novel processing mechanism. This technology will impact the steel, aluminum, chemical, forging, heat treating, casting, and welding industries as it will be applicable to most materials that exhibit ferromagnetism or paramagnetism.

Project Technical Milestones:

- Magnetic field processing of candidate ferrous alloys (FY02 – FY04, in-progress).
- Thermodynamic evaluation and modification to incorporate magnetic field effects (FY03 - FY04, in-progress).
- Determination of material magnetization response data for high magnetic field exposures (FY04).
- Phase transformation kinetic response evaluation (FY04).
- Definition of Additional Industrial Applications of Magnetic Field Processing (FY03 - FY04, in-progress).

8. **Past Project Milestones and Accomplishments:** (Provide a brief description of progress and accomplishments to date, with specific emphasis on progress towards milestones during the past calendar year.)

Proof-of-principle experiments to accomplish the first two technical milestones defined above have been successfully accomplished whereby magnetic field processing for customizing microstructures and enhancing performance was shown. In one experiment, a ferromagnetic 85Fe-15Ni alloy was magnetically processed to see if the equilibrium volume fractions of the austenite (γ) and ferrite (α) phases could be altered from that predicted by the conventional Fe-Ni equilibrium phase diagram. This 85Fe-15Ni sample was solution heat treated and quenched to develop a metastable microstructure. The sample was then heated to nominally 500ºC while under a 29 Tesla magnetic field. A second sample was given the identical heat treatment but was not exposed to the magnetic field during the 500ºC cycle. These samples were subsequently analyzed using x-ray diffraction techniques to determine the ratio of the α/γ volume fractions for the magnetically processed sample versus the non-magnetically processed sample. This ratio yielded a value of 2.0 ± 0.1 which clearly proves that magnetic processing can yield microstructures normally unachievable through conventional heat treatment practices. Effectively the ferromagnetic phase was made more thermodynamically stable with the application of the magnetic field and this yielded less austenite in the final microstructure. Literally, the amount of austenite present in the non-magnetically processed samples was halved in the magnetically processed sample contradicting current phase diagram lever-rule predictions. Therefore, austenite can be destabilized such that the transformation to ferrite is preferred which is extremely attractive from an elimination of retained austenite perspective. These results further substantiate the hypothesis that magnetic field processing, via its thermodynamic impact on the Gibbs Free Energy of the constituent phases, enables the tailoring of microstructures and therefore properties by adding a third dimension, magnetic field strength, to the classically two-dimensional temperature-composition phase diagram space for these materials. This thermodynamic effect has been shown only for a limited case and therefore future experiments are planned in a new equipment set-up that will allow the definition of this significant new processing methodology for isothermal and continuous cooling conditions.

Another experiment was conducted whereby room temperature magnetic field processing was studied to determine whether residual stresses that existed due to prior fabrication or heat treatment could be reduced or eliminated. For this study, 52100 alloy steel samples were machined and exposed to either a 1 or 6 Tesla magnetic field. Initially the samples had been solution heat treated and oil quenched to form quenched martensite. Some specimens were tempered and others received no temper treatment prior to magnetic field processing. The residual stresses before and after magnetic processing were determined via conventional x-ray diffraction methods. The results for both of these conditions on a limited number of samples indicate that indeed these quenched-in residual stresses could be reduced through magnetic processing. These results have significant ramifications since residual stress abatement is feasible in as-fabricated components or in in-service parts that have developed these during their life cycle (e.g., through thermal cycling). Life extension and higher initial allowable design stresses may be viable through the application of magnetic field processing for residual stress relief.

9. **Planned Future Milestones:** (Outline your R&D plans and schedule for the remainder of the project, with specific emphasis on plans for the next calendar year.)

The broad impact of the thermodynamic effect of magnetic processing for developing novel microstructures with enhanced performance has been shown only for a limited case and therefore future experiments will be conducted in a new equipment set-up that will allow the scoping out of the design space of this significant new processing methodology for both isothermal and continuous cooling conditions. Additional ferromagnetic alloys will be evaluated (such as 1050 alloy steel) to determine whether magnetic processing during isothermal heat treatment can yield unique chemistries (e.g., higher carbon content in the ferrite phase) for the equilibrium constituent phases in addition to altering the relative volume fractions of these alloys. Also, liquid to solid phase transformations will be investigated (e.g., in cast iron) in FY'04 to determine whether unique solidification morphologies and microstructures can be achieved. In addition, the use of commercial codes such as ThermoCalc will be evaluated and expanded to include an evaluation of the influence of an applied field on the phase equilibria (stability as defined by the Gibbs Free Energy and chemical potentials) of ferrous alloys with the ability to extend this capability to more general ferromagnetic, paramagnetic, and diamagnetic materials of relevance to the IOF. Finally, the magnetization response of materials to ultrahigh magnetic fields will be measured so that these data can be input into a thermodynamic simulation code incorporating magnetic field effect factors. This task is scheduled for FY'04.

10. **Issues/Barriers:** (Provide a brief description of any technical problems or barriers encountered and how these problems have been or will be resolved or significant deviations from original scope and/or budget.)

A key barrier existed at the initiation of this research effort which has been removed. Since the use of ultrahigh magnetic field processing for developing customized microstructures and enhanced performance in materials had not been studied before, experimental facilities did not exist that were robust enough to study the influence of magnetic exposure under controlled isothermal and continuous cooling conditions. Although this proved to be a major constraint during the first year of this project, efforts this current FY has been focused at developing a closed-loop control induction heating system that is LabView software driven and that enables precise magnetic-thermal processing paths to be programmed and executed in an existing ultrahigh magnet system. This new system is being used during the latter part of FY'03 to demonstrate the concepts of this new technology approach for materials processing.

11. **Intended Market and Commercialization Plans/Progress:**

Industrial companies expressing interest in this technology include Cummins Inc. (ferrous alloys), Dura-Bar (continuous cast iron), Southwire (power transmission cables), and Timken (ferrous applications). In addition, discussions have been held with a major superconducting magnet manufacturer, Cryomagnetics, Inc., to insure the viability of having commercial magnet systems available in the future for implementation of this technology. One example of an energy savings and cost-reducing application is the elimination of cryogenic treating or double temper heat treatment cycles to eliminate retained austenite in quenched steels. Another significant application is the utilization of magnetic field processing for the reduction of residual stresses in fabricated or in-service components for the purpose of life extension or increased allowable component design stresses.

Once the broad viability of this technology concept has been documented in this Laboratory-led IMF project, future Industry-led collaborations via the IMF Program will be pursued and accomplished for specific industrial applications and commercialization.

12. **Patents, publications, presentations:** (Please list number and reference, if applicable.)

Two patent disclosures have been prepared for this magnetic processing technology:

U.S. Patent Application: *"Method for Residual Stress Relief and Retained Austenite Destabilization"*, Gerard M. Ludtka, filed on August 13, 2002.

UT-Battelle (ORNL) Invention Disclosure ID 0916, S-96,666: *"Magnetic Field Processing for Customizing Microstructures and Properties in Materials"*, Gerard M. Ludtka, Gail M. Ludtka, Roger A. Kisner, and John B. Wilgen, Elected for patent preparation and submission.

Highlight

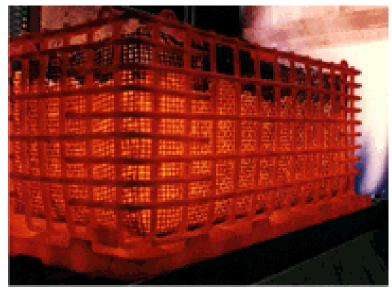
Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance

OBJECTIVE: A new high-payoff industrial processing methodology whereby alloys and microstructures with superior properties will be developed that normally would be impossible to achieve with conventional thermomechanical processing techniques.

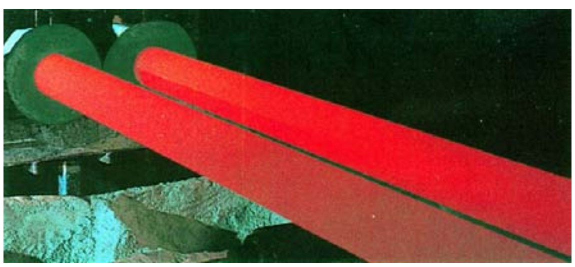
GOAL: Demonstrate and document the influence of ultra-high magnetic field processing on the phase equilibria in ferrous alloys.

BENEFITS:

- New class of materials with novel microstructures and superior properties.
- Enhanced phase transformation kinetics.
- New industrial processing methodology.
- Major manufacturing cost savings, reduced scrap, energy savings, and environmental benefits.
- The elimination of the final normalization heat treatment step through magnetic processing for bar and rod product alone would yield an energy savings of 3 trillion BTU's.



Heat Treating & Steel Applications



CASTING: Continuous Cast Iron Bar Stock

STATUS:

- Demonstrated a major effect of magnetic field processing on the phase equilibria and microstructure for a ferromagnetic material.
- Ambient temperature residual stress reduction shown for magnetic processing.
- Developed a unique capability/facility to study magnetic field processing under computer-controlled isothermal or continuous cooling conditions.

Project Partners and Interested Industrial Collaborators:

- Cummins Inc., Roger D. England
- Florida State University, Prof. Peter Kalu
- Dura-Bar, Timken, Southwire, Cryomagnetics, Inc., and Kettering University

Industrial Materials for the Future Impact Areas:

- Steel, Aluminum, Chemical, Forging, Heat-treating, Casting, and Welding industries.

Forging